

A Method and a Graphical User Interface for the Creation of an Azimuth-Track-Level Look-Up Table

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The alidades of the beam-waveguide (BWG) antennas are mounted on wheels that rotate around an imperfect track. The uneven azimuth track causes antenna deformations, which reduce pointing accuracy. The pointing errors caused by the track irregularities are repeatable and can therefore be calibrated. The effects of the irregularities in the azimuth track can continually be corrected for using a look-up table created by the interface presented here. The table is then fed into the antenna monitor and control (along with the systematic error model and predicts) to modify the pointing commands.

This article describes the stages of processing that the inclinometer data undergo, including the verification of repeatability, smoothing, slow trend removal, resampling, and adjustment to a standard format. From the processed data, the interface creates the look-up table in a simple and straightforward manner.

I. Introduction

The alidades of the beam-waveguide (BWG) antennas are mounted on wheels that move on a circular track, allowing rotation about the azimuth axis. The azimuth track is not perfectly flat. Its profile was measured at the DSS-26 antenna and is shown in Fig. 1. The level deviations should not exceed 0.040 in. (1 mm), and the actual profile deviation was 0.047 in. (1.2 mm) at its largest. An uneven azimuth track causes antenna tilts and flexible deformations, which reduce the antenna pointing accuracy during tracking.

The results of a finite-element analysis illustrating the alidade deformations due to a single wheel lift are shown in Fig. 2. These deformations are small and repeatable so that the errors can be calibrated and corrected for. Inclinometers have been placed high on the alidade structure to measure structural twisting of the elevation axis due to track irregularity.

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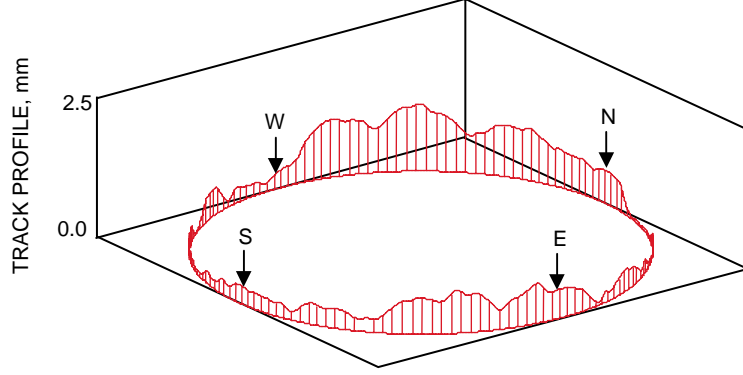


Fig. 1. Track profile of the DSS-26 antenna.

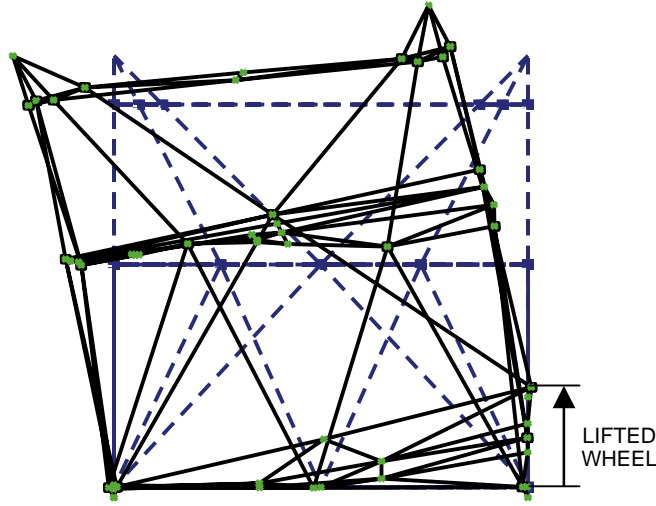


Fig. 2. Alidade deformations due to the wheel lift, with the dashed lines indicating the undeformed state and the solid lines the deformed state.

The x-y-z coordinate system is shown in Fig. 3. The x-axis is the antenna elevation axis directed from inclinometer 2 to inclinometer 1. The vertical axis oriented downward is the z-direction. The horizontal axis orthogonal to the x- and z-axes, oriented to define a right-handed coordinate system, is the y-direction. Measuring the tilts of the alidade structure at predetermined points and processing the data provide alidade rotations in the x-, y-, and z-directions as a function of azimuth position (this function is called the look-up table) and, consequently, pointing errors as a function of the antenna azimuth position.

The measurements, data processing, and look-up table creation were described in [1]. The present article expands upon the previous data-processing requirements to obtain a look-up table of greater repeatability and accuracy. It also describes the interface that makes the creation of the look-up table user friendly with a simple format. The software and graphical user interface (GUI) presented here are generic and not specific to a single antenna. Given data from four inclinometers, their relative positions, and azimuth encoder data, the GUI can be used for an arbitrary antenna.

II. Instrumentation

The data are collected with inclinometers at four antenna locations, as shown in Fig. 3. Each inclinometer measures the x- and y-tilts. To create a look-up table, the x-tilts of all four inclinometers

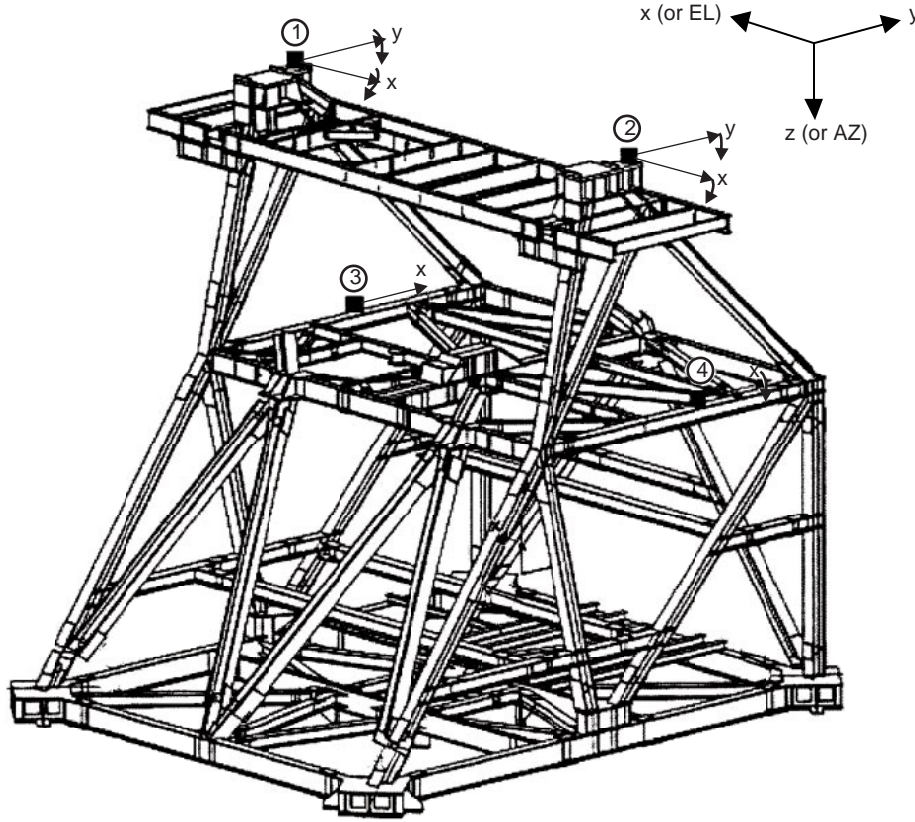


Fig. 3. Inclinometer locations.

and y-tilt of inclinometer 2 are combined as described below. The look-up table is computed at tenth-degree intervals for azimuth angles from 0 to 360 deg. Typically, however, data are collected at 2 Hz while the antenna rotates at 50 mdeg/s, so the inclinometer data are sampled every 0.025 deg of motion and need to be resampled. Also, the azimuth angle is adjusted to the $[0, 360]$ deg segment and cropped to fit the segment exactly.

The inclinometer data are noisy and contain occasional spikes. The noise must be filtered out, and the spikes removed. The data-collection process lasts more than 1 hour, long enough for the antenna structure to be affected by the environmental temperature changes. These changes are visible in the inclinometer data as slowly varying trends. The slow trends are identified in the data Fourier transforms as the low-frequency components. These components are reconstructed in the angle domain and subtracted from the data, with no evidence of trends in the new data. Also, the amplitude and phase of the antenna vertical axis tilt are verified and extracted from the data.

III. Data Acquisition Requirements

The locations of the inclinometers are shown in Fig. 3. The inclinometer data are measured while the antenna rotates in azimuth at the rate of 50 mdeg/s and sampled at a 2 Hz frequency, from one extreme azimuth position (usually -10 deg) to another (usually 359 deg) to cover at least 365 deg of rotation. The tiltmeters are on high gain with the filter off. The data are collected while moving clockwise and counterclockwise. At least two sets of encoder and inclinometer data (x- and y-tilts) are collected (four are advisable). The data are saved as a table consisting of nine or more columns in a file called filename.mat.

The distances h (height from the azimuth track to inclinometer 1) and l (distance between inclinometers 1 and 2) in consistent units also are required. The following restrictions must also be met: the antenna must undergo a full rotation continuously in one direction; inclinometers must be calibrated prior to data collection; and encoder and inclinometer data must be synchronous. Pointing errors due to azimuth track irregularities are independent of elevation position (see [1]), but varying the elevation angle while rotating in azimuth may introduce new torques on the structure and, hence, must be avoided.

The data description unit of the GUI requires typing the following information:

- (1) Location of the data file
- (2) Location in which to save the new look-up table
- (3) Location of the existing look-up table (if any)
- (4) Rate of rotation of the antenna during data collection
- (5) Sampling rate of the data collection
- (6) Ratio of the inclinometer location height to width, h/l

The following inclinometer data are used to create the look-up table:

- (1) Inclinometer 1, direction x
- (2) Inclinometer 2, direction x
- (3) Inclinometer 2, direction y
- (4) Inclinometer 3, direction x
- (5) Inclinometer 4, direction x

IV. Data Processing

The data processing consists of five steps: (1) process raw data, (2) filter, (3) move the negative segment, (4) perform a Fourier transform, and (5) match the tilt at 0 and 360 deg.

Each step consists of several processes, as described in the following subsections.

A. First Step (Process Raw Data)

This step involves reversal of the encoder and inclinometer data, if necessary, so that the encoder trend is clockwise; adjusting the azimuth range from the measured azimuth angle range to the range of $[0, 360]$ deg, guaranteeing monotonic encoder data; removing encoder and inclinometer data whenever the antenna is stationary (here the antenna is considered stationary if the encoder data vary approximately less than a hundredth of a mdeg of rotation per sample); and verifying that there are at least 365 deg of rotation data (there will be further cropping of 80 points after the filtering step).

The x-tilts of the second inclinometer, *inc2x*, before and after the first stage of processing are shown in Fig. 4 as an illustration of the above procedure.

B. Second Step (Filter)

This step begins with removal of inclinometer spikes (of magnitude larger than 30 mdeg), and is followed by inclinometer data smoothing using a zero phase forward and reverse digital filter with a 20 point window. The i th filtered value, y_{ffi} , of a series, y_i , is obtained by forward averaging:

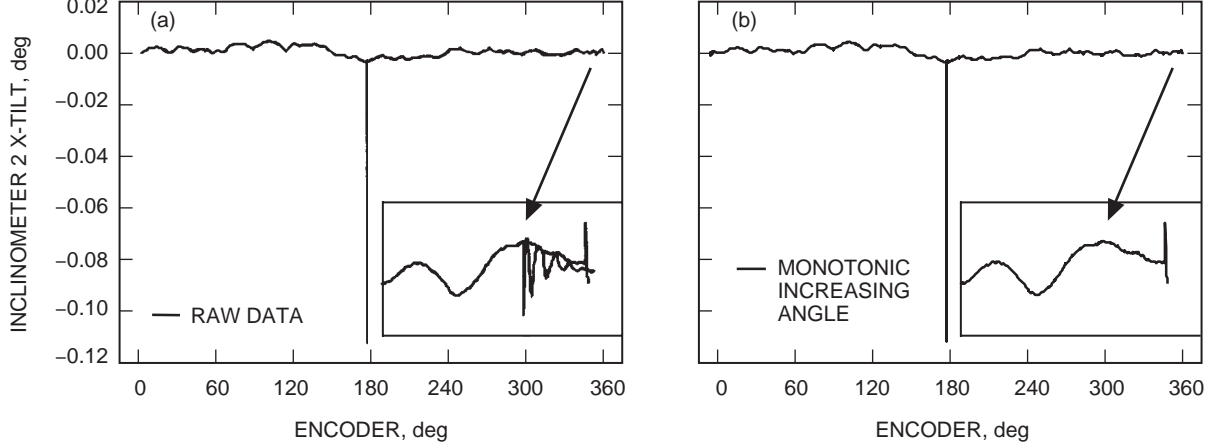


Fig. 4. Data for the second inclinometer x-tilt: (a) before step 1 and (b) after step 1.

$$y_{fi} = \frac{1}{n} \sum_{j=0}^{n-1} y_{i-j}, \quad i = n + 1 : 1 : N + 2n - 1 \quad (1a)$$

and subsequent backward averaging:

$$y_{ffi} = \frac{1}{n} \sum_{j=0}^{n-1} y_{f(i+j)}, \quad i = N + n + 1 : -1 : 1 \quad (1b)$$

where $n = 20$ and $N + 2n$ is the length of the data. The result has zero phase distortion, and magnitude is smoothed. Forty points are cropped from each end of the inclinometer and encoder data to minimize startup and ending transients.

The *inc2x* data before and after this stage are shown in Fig. 5, which shows a smoothed curve without spikes after filtering.

C. Third Step (Move the Negative Segment)

In this step, the negative segment of data is shifted to the end (e.g., data that ranged from -10 to 355 deg become $0:360$ deg by throwing away the $[-10, -5]$ deg segment and moving the $[-5, 0]$ deg segment to right after 355 deg).

The *inc2x* data before and after this stage are shown in Fig. 6. The figure shows the processed data that fit the azimuth angle segment of $[0, 360]$ deg.

D. Fourth Step (Fourier Transform)

In this step, the time-dependent thermal effects are removed by zeroing out the fundamental, second harmonic, and third harmonic terms of the transformed data using Matlab's fast Fourier transform algorithm. The removal does not impact the antenna pointing since the removed harmonics are the part of the pointing model that consists of a fourth-order spherical harmonic expansion. Also, in this step encoder spikes are removed, and the processed inclinometer data are interpolated for a 0 - to 360 -deg range, sampled every 0.1 deg. Encoder spikes in the data are created by software imperfections, and the spiked values are replaced with the average of the neighboring values.

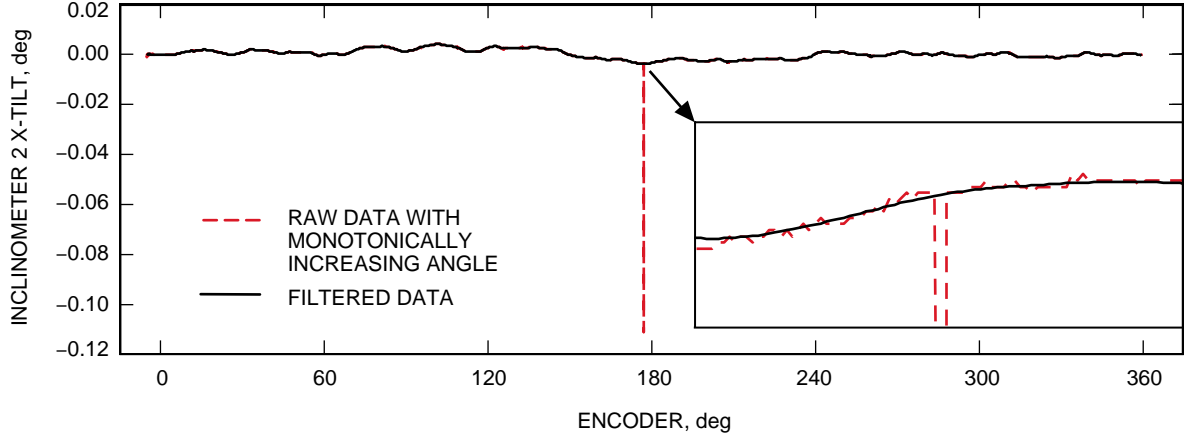


Fig. 5. Data before and after step 2, with the spikes removed and the data smoothed.

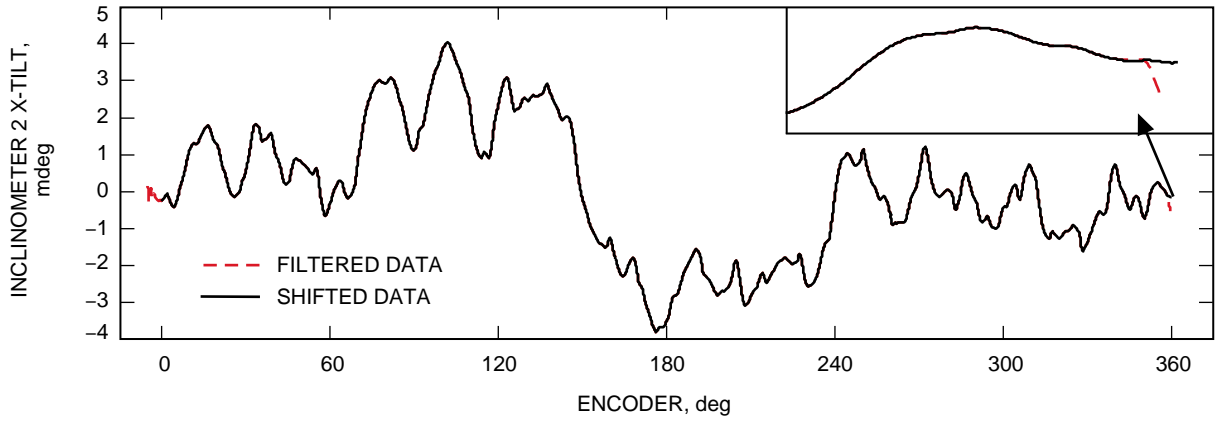


Fig. 6. Data before and after step 3; after the step 3 processing, the data fit the azimuth-angle segment of $[0, 360]$ deg.

Let the coefficients of the Fourier transform be denoted $a_i, i = 0, 1, 2, \dots$. The zero component represents the constant offset. The harmonic terms $h_i, i = 0, 1, 2, 3$ are obtained from the Fourier coefficients as follows:

$$\left. \begin{aligned} h_i(\alpha) &= \frac{2}{N} (a_{ri} \cos(i\kappa\alpha) - a_{ii} \sin(i\kappa\alpha)) \\ \alpha &= 0 : d\alpha : 360 - d\alpha \end{aligned} \right\} \quad (2a)$$

where

$$\left. \begin{aligned} a_{ri} &= \text{Re}(a_i) \\ a_{ii} &= \text{Im}(a_i) \\ \kappa &= \frac{\pi}{180} \\ d\alpha &= \frac{360}{N} \end{aligned} \right\} \quad (2b)$$

where N is the number of samples, α is the encoder angle in degrees, and $d\alpha$ is the encoder sampling interval.

The three harmonics that were removed from the inclinometer data are shown in Figs. 7(a) through 7(c), and their sum is given by the dashed line in Fig. 7(d). In the latter figure, the inclinometer data are shown by the solid line. The superposition shows that the low-rate trend indeed was recovered.

The *inc2x* data before and after this stage are shown in Fig. 8. The figure shows that the low-frequency trends were removed.

E. Fifth step (Match Tilt at 0 and 360 deg)

This final step of processing done on each inclinometer axis puts the data in a standard format for easy comparison with other data sets. The linear trend is removed so that 0 deg and 360 deg both have 0 deg of tilt, and the results are saved to the appropriate column of the “temp” matrix in the file *tofile.mat*. The constant offset can be removed, since it is included in the pointing model. The linear trend implies a multiple-valued function for an azimuth of 0 deg (=360 deg) and is an artifact caused by a slow thermal drift present during the measurements.

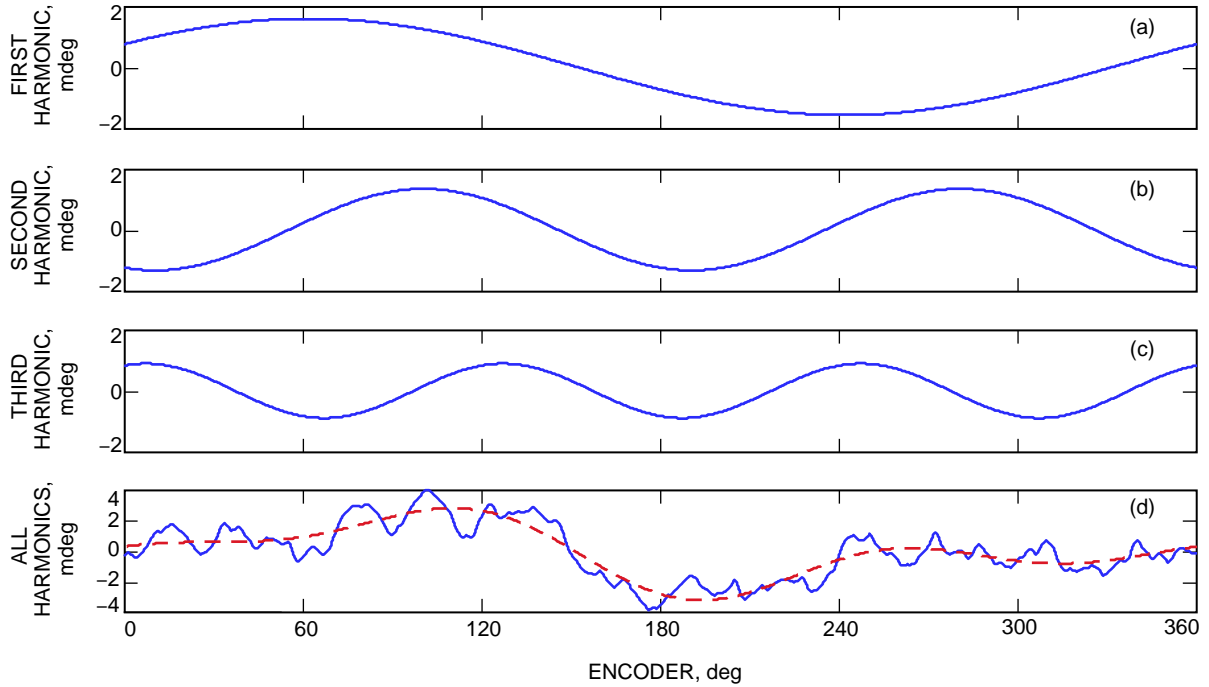


Fig. 7. Trend removal of (a) the first harmonic, (b) the second harmonic, (c) the third harmonic, and (d) the sum of the first three harmonics (dashed line) on top of the inclinometer data (solid line).

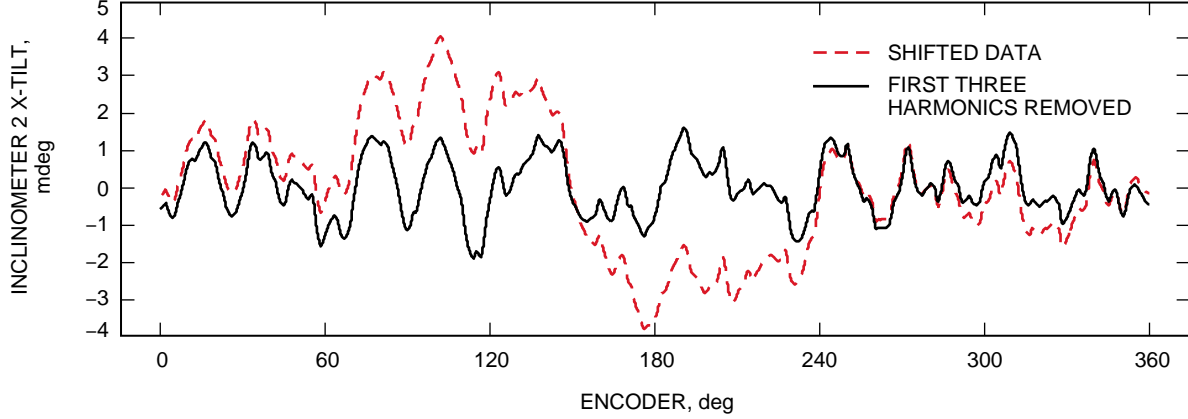


Fig. 8. Data before and after step 4; after step 4, the slow trends were removed.

The *inc2x* data before and after this stage are shown in Fig. 9. The figure shows that the remaining linear trend was removed and that the data begin and end at 0 deg of tilt.

For brevity, not all of the above results are displayed while running the GUI, although the results are saved in the “step” structure in the file *guirun.mat* (this file is overwritten at the first calculation of inclinometer 1). It is advisable to monitor the processing so that reasonable output is ensured. Note that the user does not have any say regarding the processing variables, but, at the end, the user may select from a few data sets that which appears to be the cleanest and then compute a look-up table for that data set.

V. Look-Up Table Creation

The look-up table consists of three rotations of the top of the alidade, denoted dx , dy , and dz . The dx rotation is in the direction of elevation angle and is positive in the upward direction. The dz rotation is in the direction of the azimuth angle and is positive in the clockwise direction. The dy rotation is orthogonal to the dx and dz angles and is directed and sensed to define a right-handed coordinate system. The coordinate system for these rotations is shown in Fig. 3. Note that the orientation of this system is different from that in [2] and also different from the customary DSN coordinate system. It is consistent with the data-collection coordinates.

The three-axis look-up table is created using the x-axis tilts (*inc1x*, *inc2x*, *inc3x*, and *inc4x*) at four locations on the antenna structure, as well as the y-axis tilt of the inclinometer at the elevation encoder (*inc2y*) (see Fig. 3 for the locations and reference axes). Note that the downward inclinometer tilts are positive and that the x-tilts of inclinometers 3 and 4 are parallel to y-tilts of inclinometers 1 and 2. The alidade rotations are obtained in the following manner (see [1]):

$$dx = inc2y \quad (3a)$$

$$dy = -0.5(inc1x + inc2x) \quad (3b)$$

$$dz = \frac{h}{l}(inc3x - inc4x) \quad (3c)$$

The look-up table is plotted in Fig. 10.

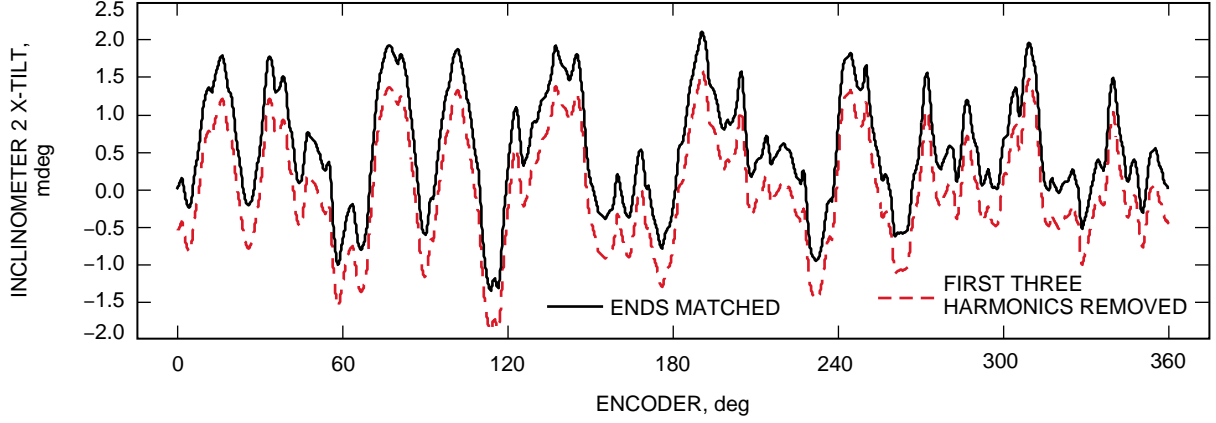


Fig. 9. Data before and after step 5; after step 5, the remaining linear trend was removed, and the data begin and end at 0.

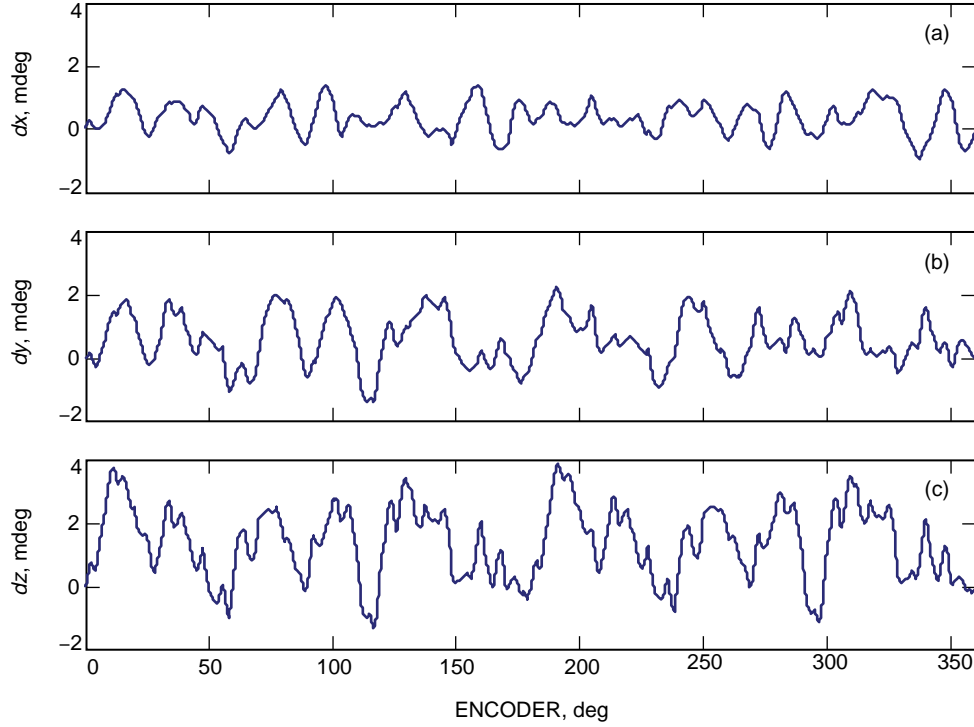


Fig. 10. The look-up table: alidade (a) dx , (b) dy , and (c) dz rotations versus azimuth encoder angle.

For the given antenna elevation position, θ , the azimuth, cross-elevation, and elevation pointing-error corrections are obtained from the look-up table components as

$$\Delta_{el} = dx \quad (4a)$$

$$\Delta_{xel} = dz \cos(\theta) - dy \sin(\theta) \quad (4b)$$

$$\Delta_{az} = dz - dy \tan(\theta) \quad (4c)$$

Figure 11 illustrates the derivation of the cross-elevation error. The pointing-error corrections for elevation angle $\theta = 60$ deg are plotted in Fig. 12.

VI. GUI Description

The goal was to design a tool that requires only a very basic understanding of the processes at hand, with little or no preprocessing of the data, to filter the data and uncover the repeatable alidade rotations and easily create a look-up table. This interface contains three sections (see Fig. 13): data description, data processing, and look-up table generation, all of which are on the bottom half of the window. Additionally, three visual sections contain a Cartesian plot in the interface, where the data are plotted during the processing phase, and external plots A and B, which display processed inclinometer tilts and the look-up table, respectively. A vertically exaggerated figure of the azimuth track irregularities, created with data obtained from inclinometers mounted at the track level, is shown on the top of the interface.

A. Data Description Section

Before processing a data set, some of the quantitative file characteristics must be entered so that the data may be processed correctly. This section adds to the versatility of the GUI.

Do the following to enter data in the GUI (see Fig. 14):

- (1) Enter the data set into the “raw data file” editable text box.
- (2) Enter a new filename into the “save look-up table to” box. A silent warning will be made in the Matlab command window if this file already exists.
- (3) Verify that the antenna-rotation rate and the data-collection rate are correct. These values affect data cropping and will produce errors if inaccurate in either direction.
- (4) Enter the distance ratio, h/l , using consistent units.

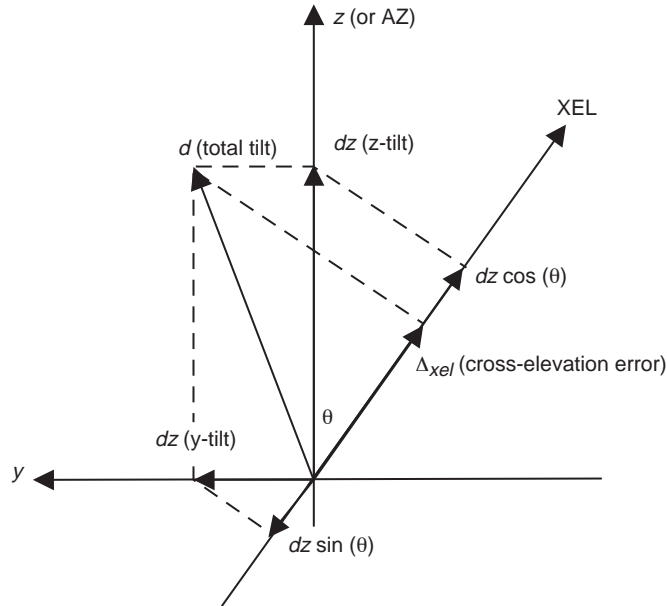


Fig. 11. Cross-elevation pointing error from the total tilt.

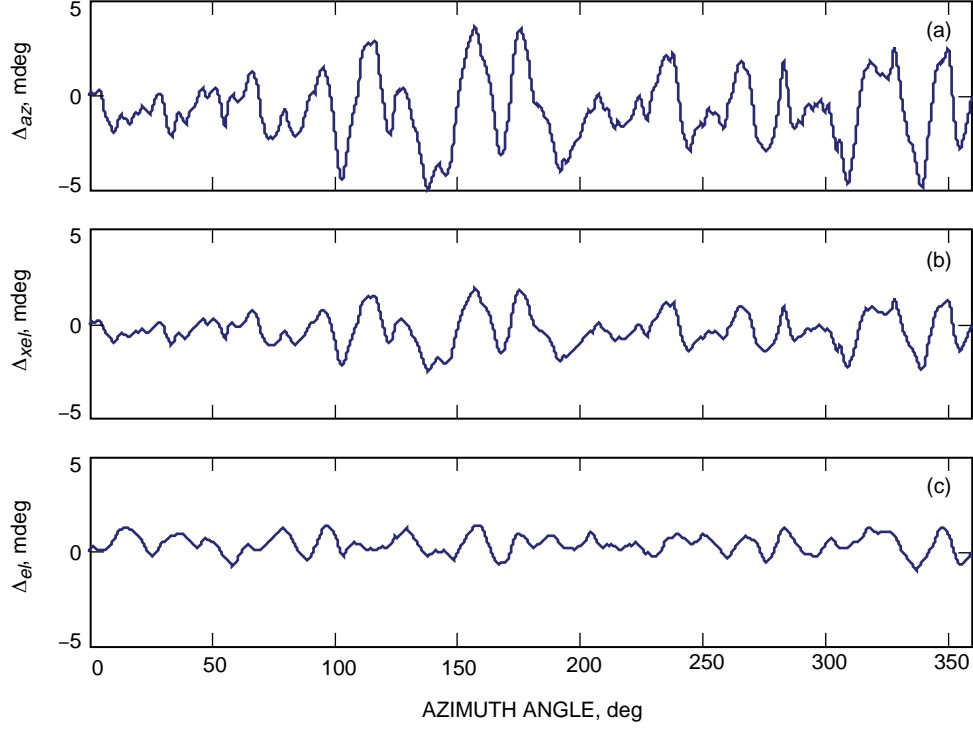


Fig. 12. Pointing-error corrections: (a) azimuth, (b) cross-elevation, (c) and elevation.

- (5) Verify that columns of data are correctly indexed.
- (6) Verify that the interface has been reset using the “reset” button.
- (7) Collect the encoder data (and related inclinometer data) with a sampling interval smaller than 100 mdeg; 30 mdeg is recommended. Thus, if the antenna rotates at the rate of v mdeg/s, and the data collection frequency is f Hz, then

$$\frac{v}{f} \leq 30 \text{ mdeg} \quad (5)$$

For the data collection, as described in Section III, $v = 50$ mdeg/s and $f = 2$ Hz, so that $v/f = 25$ mdeg.

B. Data Processing Section

This section consists of five steps, as described in Section IV and shown in Fig. 15. To uncover the true effects of the track irregularities, various filters must be used. This section of the GUI displays the effects of data processing, such as smoothing (Matlab filter `filtfilt.m`), spike removal, trend removal using Fourier transform, aligning the data from 0 to 360 deg, and interpolating the data to a standard form. For brevity, not all of the above-described results are displayed while running the GUI.

The results are saved in the “step” structure in the file `guirun.mat` (this file is overwritten at the first calculation of inclinometer 1). It is advisable to monitor the processing so that reasonable output is ensured. Note that the user does not have any say regarding the processing variables, but, at the end, the user may select from a few data sets that which appears to be the cleanest and then compute a look-up table for that data set.

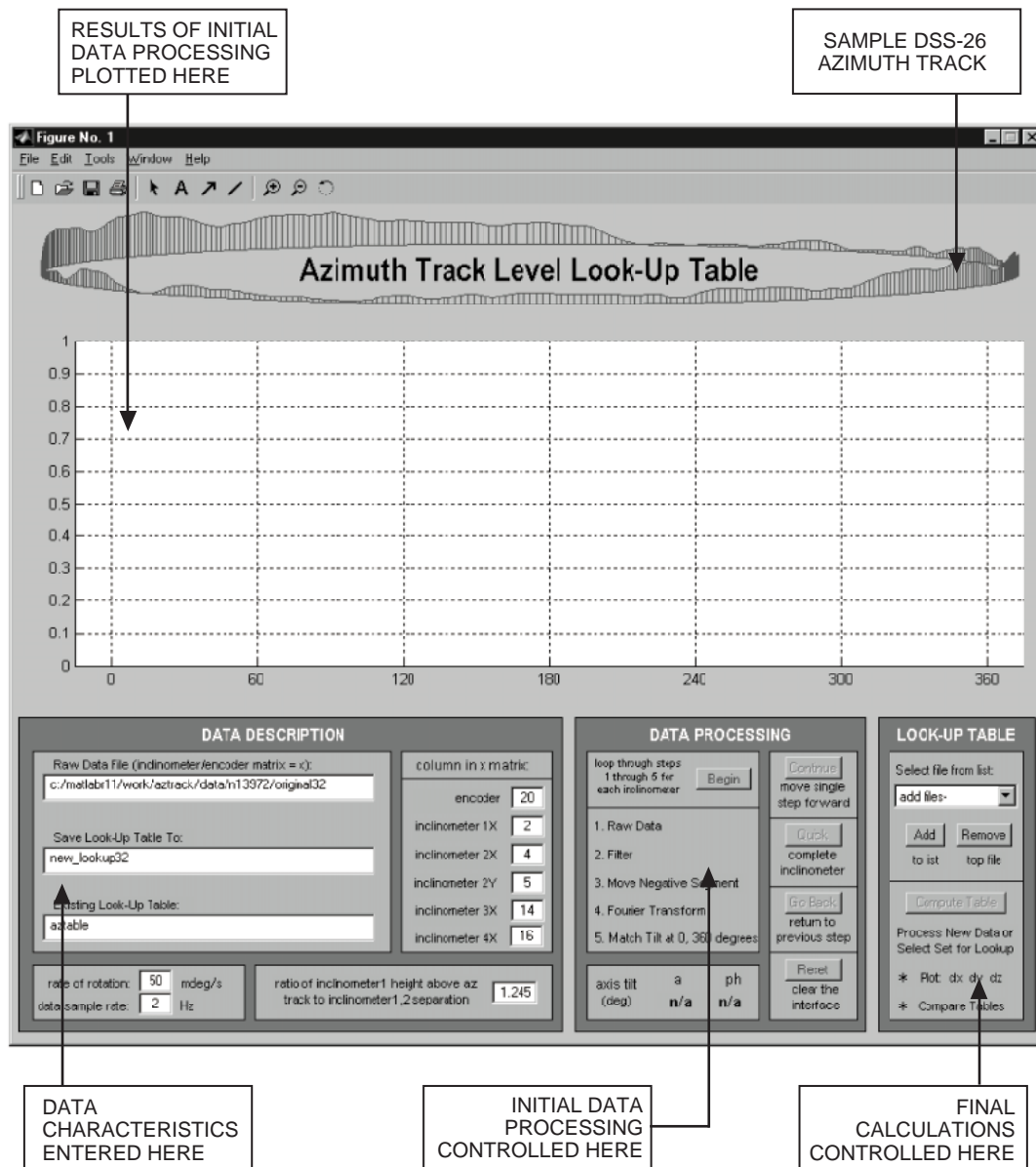


Fig. 13. Interface layout.

To run the GUI for data processing, one first enters the applicable data information and then performs the following steps to process it:

- (1) First hit the “begin” button.
- (2) Step through the computations using the “continue” button. Compute steps 1 through 5 as given in Section IV for each inclinometer axis (1x, 2x, 2y, 3x, and 4x). When run, each plot will be printed in the figure window of Fig. 15, where the solid blue line will represent the data just calculated and the dotted green line will represent the previous step. If at any of these steps an error occurs (implying that the data set is bad), the GUI need not be restarted; rather, the user may just reset the interface and continue with other data.

- (3) Alternatively, steps 1 through 5 as given in Section IV can be computed all at once, but displays of progress between steps are suppressed. In order to proceed quickly, press the “quick” button. In this case, the raw data (dotted green line) and processed data (blue line) will be plotted in the figure window of Fig. 15.
- (4) The “back” button will take a single step backwards to return to the previous step if at any time the user chooses to view the results of one or more earlier steps.
- (5) The data processed thus far will be saved in the file guirun.mat, but will be overwritten if any data file is processed further. The results of the processed data from each

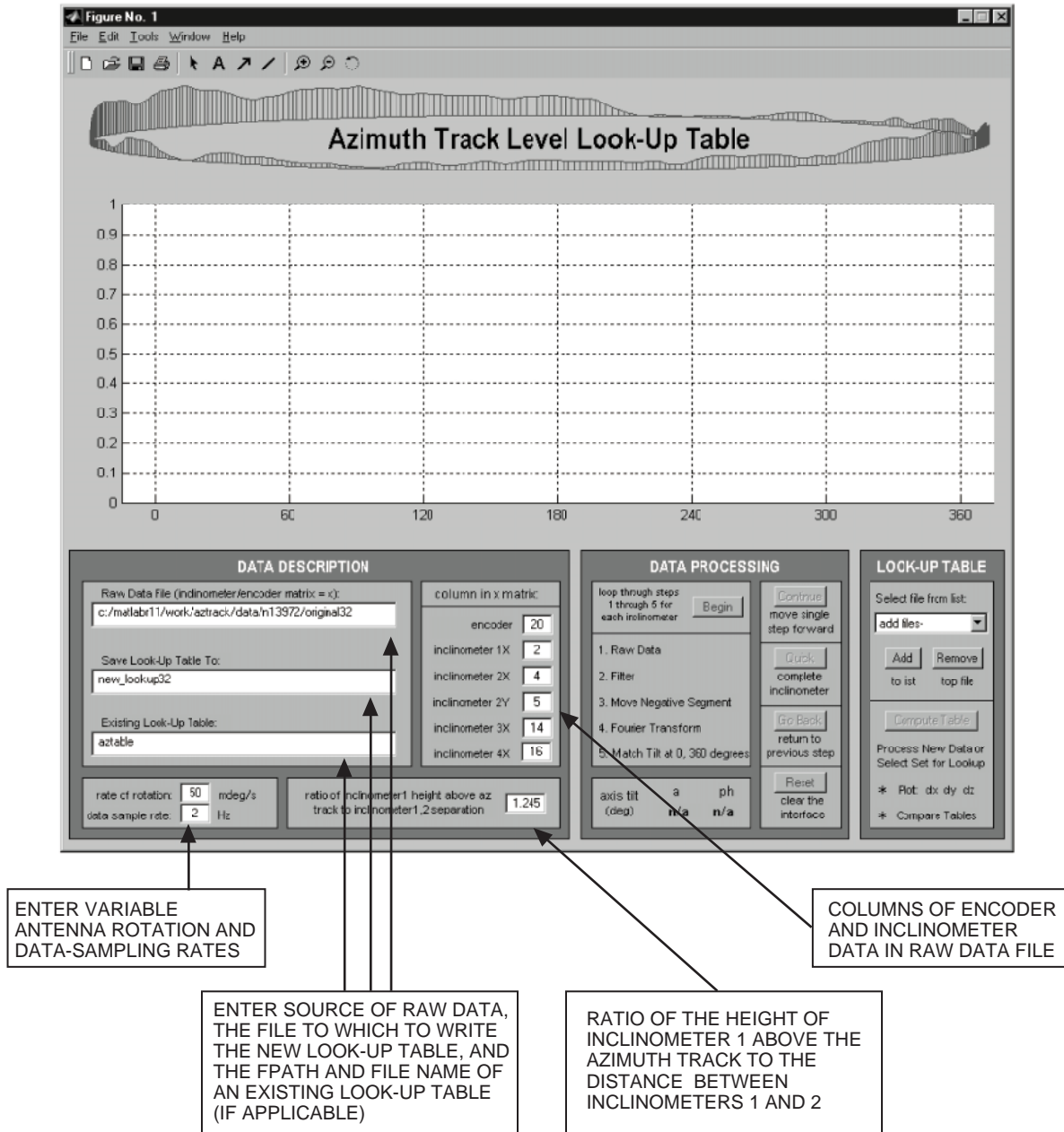


Fig. 14. Data description interface.

inclinometer axis are saved under the variable “temp” in the file in the “save to” editable text box. If the data have reached this stage in processing, the inclinometer values are stored under the look-up table pull-down list, and the individual inclinometer results are plotted in an external window, called figure A (see Fig. 16). It is from this list that the user selects a file for look-up table generation.

- (6) To process another set of data, go back to the data description, enter values corresponding to the new data set, and continue processing data sets as long as desired. It is recommended that at least three sets be compared.

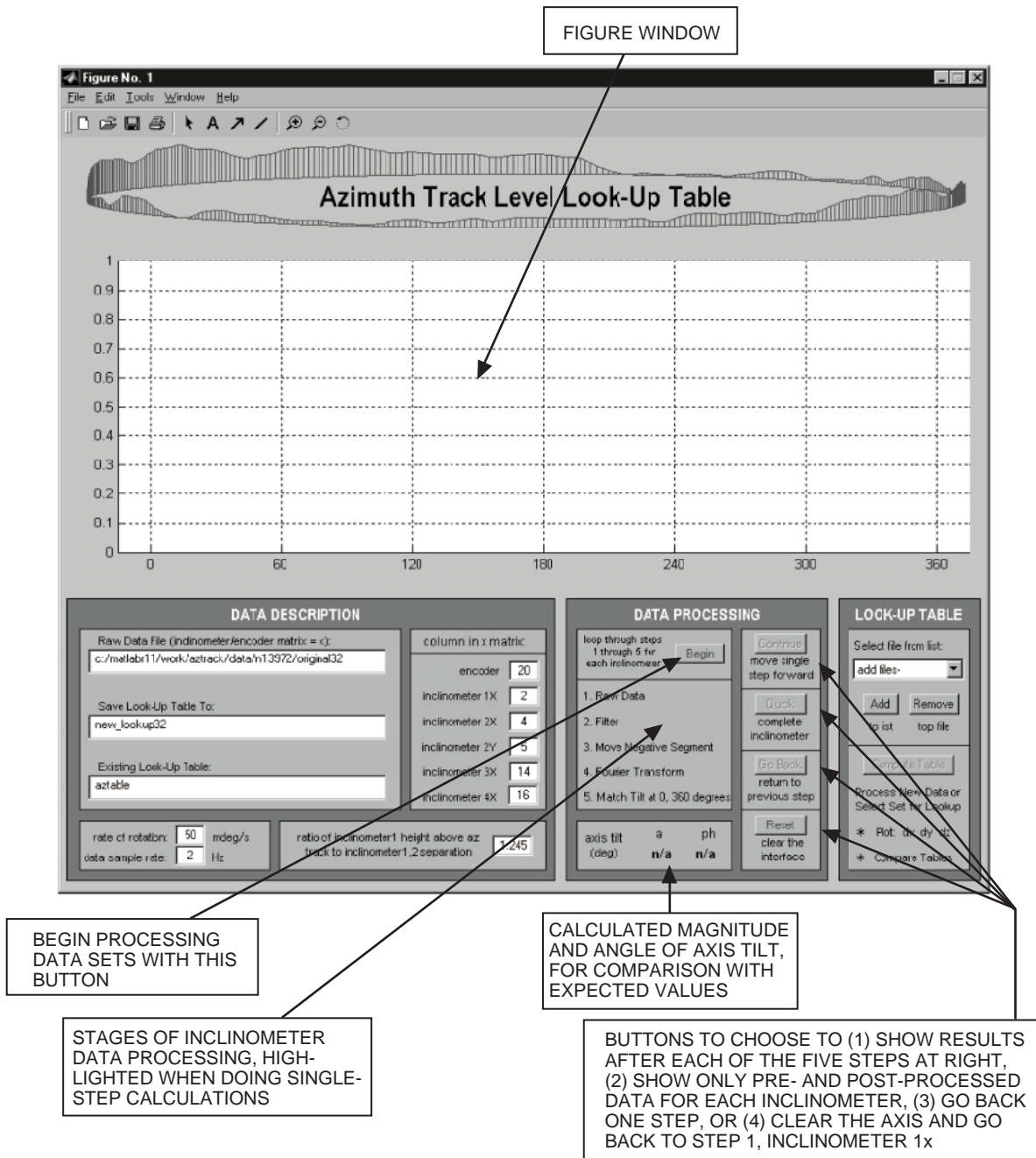


Fig. 15. Data processing interface.

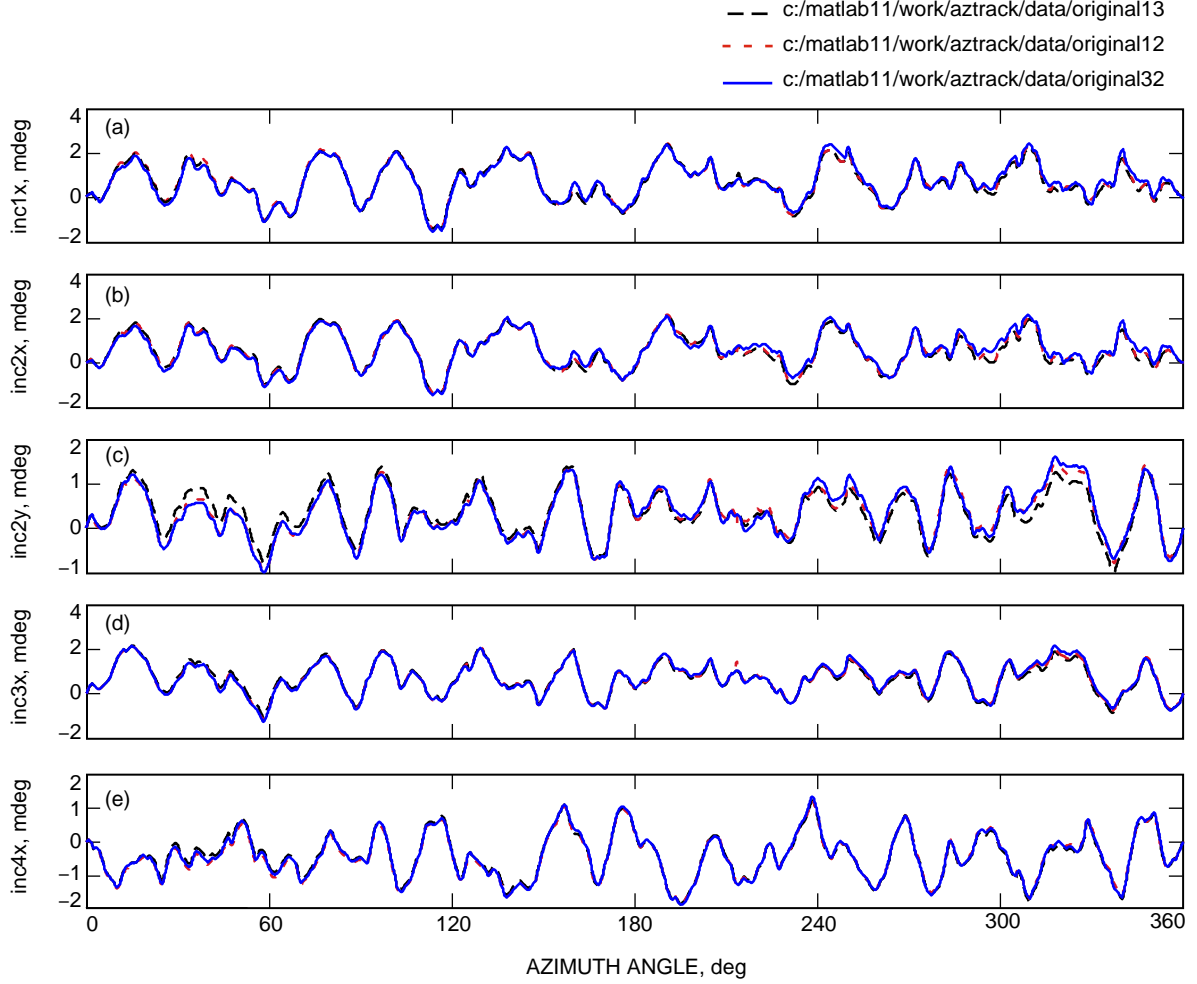


Fig. 16. Inclinometer data after processing: (a) inclinometer 1 x-axis, (b) inclinometer 2 x-axis, (c) inclinometer 2 y-axis, (d) inclinometer 3 x-axis, and (e) inclinometer 4 x-axis.

C. Look-Up Table Section

At least three complete inclinometer data sets are processed to verify the repeatability of the data. A look-up table of dx , dy , and dz is generated from the representative data set. The user may verify the similarities between the newly processed and existing look-up tables.

As data sets are processed, the results from each inclinometer will be added to a subplot of an external figure A, and the file will be added to the pull-down menu (see Fig. 17). After processing a few sets, this figure should provide the information needed to compare the different sets, and the user will select one set with which to create a look-up table. This program will then plot dx , dy , and dz , the three look-up table components, to three different axes on another figure, called figure B. These plots are shown in Fig. 10. As an optional last step, the user may choose to add an existing look-up table to these plots for comparison. The pointing-error corrections are computed from Eqs. (4a) through (4c) and are plotted in Fig. 12.

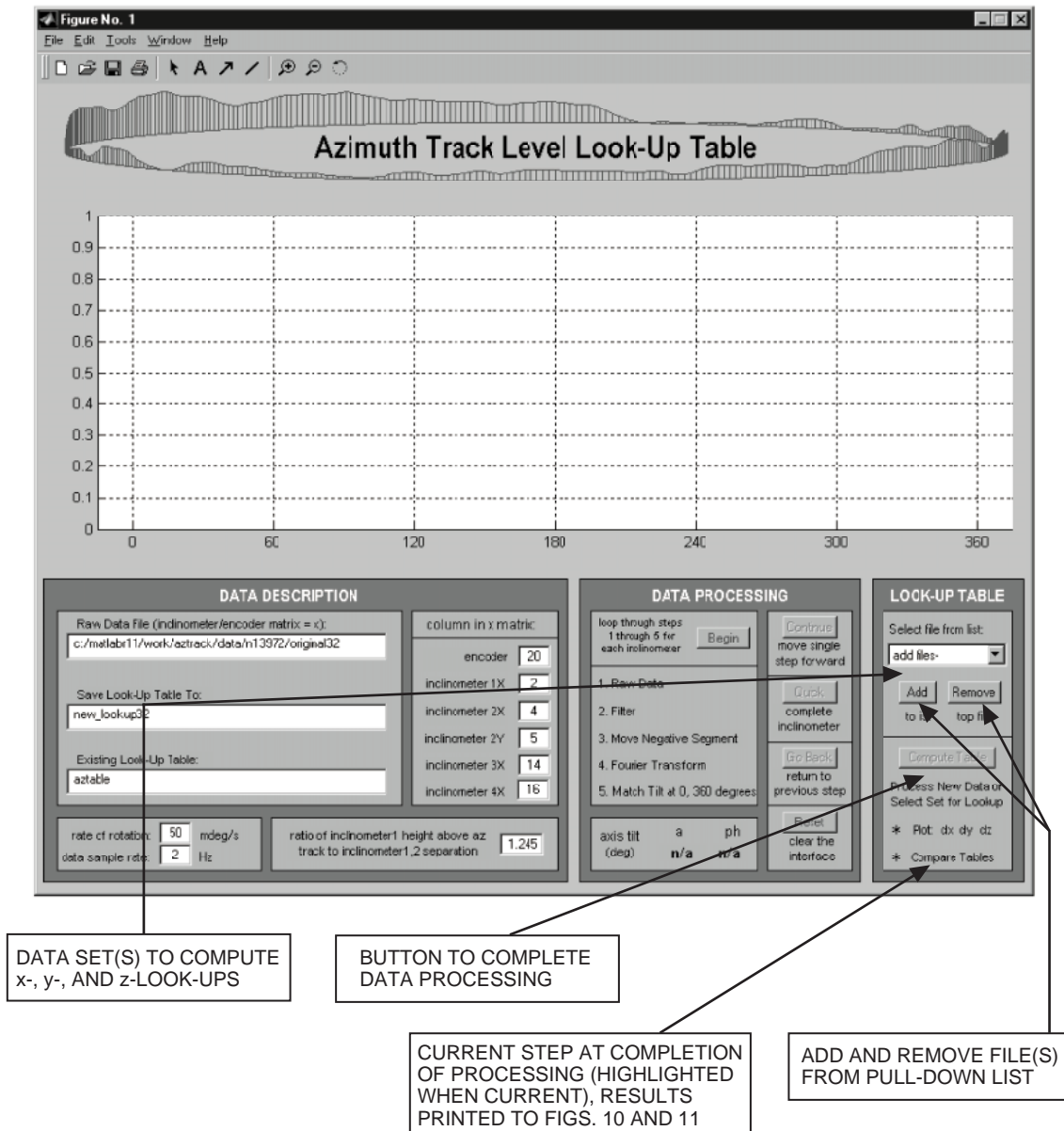


Fig. 17. Look-up table interface.

The following steps are required to run the GUI to obtain a look-up table (refer to Fig. 17):

- (1) If the figure A window has remained open throughout all data processing, each file plotted should appear in the pull-down list. If not, the user may add a file to the pull-down list manually by entering the processed data file name in the "save to" box and hitting the "add" button.
- (2) The user must select one representative data set, rejecting those with the largest deviations from the others. To choose this set, select that file from the pull-down list (verify that its name appears in the window). If desired, the user may remove the "bad" files from the pull-down list with the "remove" button.

- (3) Press the “compute table” button. The variables dx , dy , and dz will be saved to the file entered in the “save file to” box, and the plot will appear in figure B.
- (4) If an old look-up table is available, verify that it contains the variables (with these exact names) dx_{old} , dy_{old} , dz_{old} , and enc , and that they all have the same dimensions; enter the complete filename and path (if not in current directory) into the “existing look-up table” editable text box. Again press the “compute table” button. The old table is in green and the new table is in blue. For x-rotation, the closeness of the new and old look-up tables can be evaluated as follows:

$$\Delta_x = \frac{\|dx - dx_{old}\|_2}{\|dx\|_2} = \frac{\left(\sum_i (dx_i - dx_{old\ i})^2\right)^{1/2}}{\left(\sum_i dx_i^2\right)^{1/2}} \quad (6)$$

The look-up table can be compared in a similar way for the y- and z-rotations.

VII. Conclusions

This article described the processing of the field data (inclinometers and azimuth encoder) and the creation of the azimuth-track-level look-up table. It also explains the generation of the pointing-error corrections. The data processing and the creation of the look-up table are accomplished through a graphical user interface that allows a user unfamiliar with its creation procedures to proceed to the end results step by step. Although tested with the JPL BWG antennas, the GUI can be used with any antennas.

Acknowledgment

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Reference

- [1] W. Gawronski, F. Baher, and O. Quintero, “Azimuth-Track-Level Compensation to Reduce Blind-Pointing Errors of the Beam-Waveguide Antennas,” *The Telecommunications and Mission Operations Progress Report 42-139, July–September 1999*, Jet Propulsion Laboratory, Pasadena, California, pp. 1–18, November 15, 1999.
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